Magnetic susceptibility of $LaRu_3Si_2$

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Abstract

The magnetization M of $LaRu_3Si_2$ has been measured to investigate the electronic states in the normal state. The magnetization curve (M-H curve) was analyzed with assuming that it consists of an intrinsic paramagnetic part and a ferromagnetic impurity part. The estimated intrinsic magnetic susceptibility is very dependent on temperature. This is attributable to a narrow band of conduction electrons with a high density of states, which is consistent with a considerably high superconducting transition temperature T_s=6.5 K.

Key words: $LaRu_3Si_2$; mixed valence; magnetization; magnetic susceptibility

The mixed valence phenomenon and Kondo effect in a ternary rare earth compound RRu_3Si_2 (R=rare earth element) have been a matter of interest [1–4]. $CeRu_3Si_2$ becomes superconducting below the superconducting transition temperature T_s=1 K while T_s of $LaRu_3Si_2$ is as high as 6.5 K. To understand this depression of superconductivity by the localized 4f moment and the strength of hybridization between 4f and conduction electrons in $CeRu_3Si_2$, it is necessary to investigate the superconducting and magnetic properties in $LaRu_3Si_2$ without 4f electrons. In this paper, the magnetic field and temperature (T-) dependence of the magnetization M in the normal state of $LaRu_3Si_2$ is reported and the density of states (DOS) of conduction electrons is discussed.

A polycrystalline sample of $LaRu_3Si_2$ was prepared in an argon arc furnace by melting pure starting elements La, Ru and Si. The powder X-ray diffraction pattern shows that the sample is of a good single phase. The magnetization M was measured with a SQUID magnetometer.

M measured at 300 K is plotted against the applied field H (M-H curve) by closed circles in Fig. 1. The slope of this curve becomes smaller with increasing H and seems to be constant above 10 kOe. Similar behavior is observed at each measured temperature between 10 and 300 K. We consider $M=\chi H+M_{\mathrm{ferro-imp}}(H)$, where χ is the magnetic susceptibility and $M_{\mathrm{ferro-imp}}(H)$ is a magnetization of some ferromagnetic impurity. $M_{\mathrm{ferro-imp}}(H)$ is considered to saturate and be constant above 10 kOe.

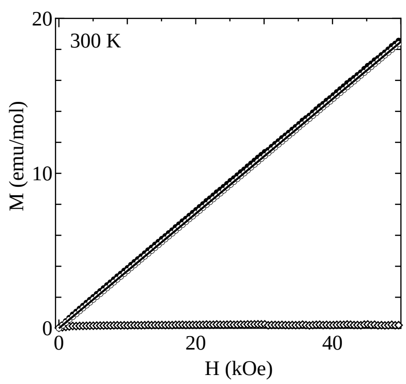

Fig. 1. Magnetization M (closed circles) measured at 300 K is decomposed into H -linear part (solid line and open circles) and impurity part $M_{\mathrm{ferro-imp}}(H)$ (open diamonds).

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χH and the saturated value of $M_{\rm ferro-imp}(H)$ are estimated by the least-squares fitting of $M = \chi H$+const. to the data points above 10 kOe. The solid line and open circles give the χH. The open diamonds show $M_{\rm ferro-imp}$ (H) obtained by subtracting χH from the raw M. The saturated value of $M_{\rm ferro-imp}(H)$=0.22 emu/mol is only about 1 % of χH= 18.5 emu/mol at 50 kOe. Therefore, M/H obtained at H=50 kOe can be used as χ. In our previous paper, we derived χ from the slope of the M- H curve above 10 kOe [5]. In this paper, we discuss the T- dependence of χ obtained from M/H measured at H=50 kOe.

In Fig. 2, the T-dependence of M/H measured at H=50 kOe is shown by open circles. M/H is T-dependent and is considered to consist of the intrinsic T-dependent part $\chi(T)$ reflecting the electronic correlation, the T-independent part χ_0 which contains the orbital contribution due to d electrons and spin contribution due to s and p electrons, and a paramagnetic impurity part $\chi_{\rm imp}(T)$=$C/(T+\theta)$. In the material which has a narrow band or shows Kondo effect, $\chi(T)$ becomes a constant $\chi(0)$ at sufficiently low T. The least-squares fitting of $C/(T+\theta)$+ const. to the data points below 60 K gives $\chi(0)+\chi_0$=4.29 10^{-4} emu/mol, C=5.54 10^{-4} K emu/mol and θ=7.23 K. These values are close to those obtained in the previous paper [5], $\chi(0)+\chi_0$=4.32 10^{-4} emu/mol and C=4.01 10^{-4} K emu/mol. $\chi(T)+\chi_0$(= χ-$\chi_{\rm imp}(T)$) shown by open triangles in Fig. 2 still depends on T at high temperatures. In general, χ of metals which have a narrow DOS or show Kondo effect shows the Pauli paramagnetism at low T and a Curie-Weiss law at high T.

In order to estimate $\chi(0)$, we plot $(\chi$-$\chi_{\rm imp}(T))T$ against T in Fig. 3. At sufficiently low T, the data points are linear to T and the slope gives $\chi(0)+\chi_0$ as discussed above. The slope of this curve becomes smaller with increasing T, and is expected to become χ_0 at sufficiently high T because $\chi(T)$ is proportional to $1/T$. The least-squares fitting of (χ-

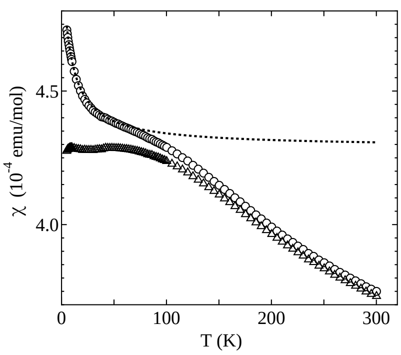

Fig. 2. Temperature dependence of χ(open circles) estimated from M/H measured at 50 kOe. The dotted curve shows the best fitted χ=$\chi(0)+\chi_0$+ $C/(T+\theta)$ below 60 K. $\chi(T)+\chi_0$ is shown by open triangles.

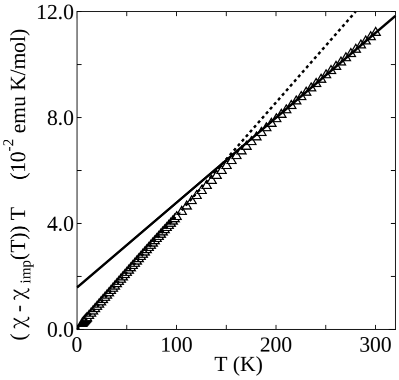

Fig. 3. Temperature dependence of $(\chi$-$\chi_{\rm imp}(T))T$. The dotted line shows the linear fitting below 60 K. The solid line shows the linear fitting above 260 K.

$\chi_{\rm imp}(T))T$=$\chi_0 T$+const. to the data points above 260 K gives χ_0=3.20 10^{-4} emu/mol. $\chi(0)$ is thus estimated to be 1.09 10^{-4} emu/mol.

If $\chi(T)$ originates mainly from the narrow band of Ru 4d electrons, we can estimate DOS of 4d electrons $N_{\rm 4d}(\varepsilon_{\rm F})$ at Fermi level using the formula of Pauli paramagnetism $\chi(0)$=2 ${\mu_{\rm B}}^2 N_{\rm 4d}(\varepsilon_{\rm F})$. $N_{\rm 4d}(\varepsilon_{\rm F})$ is obtained to be 0.56 states/eV Ru spin. This value is nearly the same as $N_{\rm 4d}(\varepsilon_{\rm F})$=1.03 states/eV Ru spin estimated in the previous paper [5]. These values are comparable to DOS of V 3d electrons $N_{\rm 3d}(\varepsilon_{\rm F})$=1.60 states/eV V spin in C15 Laves phase HfV2 [6,7], in which a strongly T-dependent χ originates from the narrow band with high DOS. The large $N_{\rm 4d}(\varepsilon_{\rm F})$ may explain also the considerably high $T_{\rm s}$ of $LaRu_3Si_2$.

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